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Prediction and Experimental Validation of an Impact Energy Threshold for Mechanical Surface Smoothing

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Abstract

Dynamic processes like machine hammer peening generate a smoothing of tool surfaces, an increase in hardness and residual compressive stresses in the surface layer. So far, it is not possible to determine the energy threshold needed to smooth a rough surface based on tool parameters and workpiece characteristics. Thus, this paper focuses on the definition of an energy threshold as well as the derivation of an analytical equation to calculate the energy demand for plastic deformation. The method is validated by experimental investigations. It is shown that the defined energy threshold for mechanical surface smoothing corresponds with the experimental data.

Keywords: Surface Modification, Energy, Machine Hammer Peening

1. Introduction

The process stability of deep drawing operations is heavily affected by the surface integrity of the dies. Usually, the final surface quality of the tools is produced by manual polishing. However, automated processes have recently begun to replace manual finishing and can lead to significant cost savings. This paper focuses on the mechanical surface treatment technology of machine hammer peening (MHP).

MHP technology is characterized by an electro-magnetic [1], pneumatic [2] or piezo-electric [3] driven hammer head which is repeatedly accelerated against the surface to be treated. The kinetic energy is transferred into the material and allows smoothing of surface asperities [4]. At the same time, the hardness of the surface layer is increased [5] and residual compressive stresses are induced [6].

2. Scope of investigation

In order to provide a desired surface topography after MHP, the process parameters need to be adjusted to the material of the workpiece. A small hammering energy can result in an insufficient smoothing of the surface asperities, while an exaggerated energy level causes surface defects [7].

Nomenclature

r_H	Radius of the hammerhead / spherical indenter
r_I	Radius of indentation
D_P	Depth of penetration
R_z	Surface roughness of the specimen
r_I	Radius of indentation area
E_T	Threshold energy
$R_{p0,2}$	Yield strength of workpiece material
R_{pI}	Yield strength of workpiece during impact conditions
E_E	Energy needed for elastic deformation
E_P	Energy needed for plastic deformation
e	Coefficient of restitution
F_M	Mean forming force
A_I	Area of indentation
Y_{SM}	Mean flow stress
φ	Degree of deformation
E_1	Young's-Modulus of specimen
E_2	Young's-Modulus of spherical indenter
Rz_I	Roughness of spherical indenter
η	Forming efficiency
s	Step over distance

However, so far there is no model that allows for the prediction of the surface deformation from easily measured

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parameters like the tool geometry, workpiece characteristics, including initial roughness and mechanical properties. Therefore, this study focuses on determining the energy input required for a successful smoothing of surface asperities by MHP. Results may also be applicable to other energy related surface treatment technologies.

3. Approach

First, existing work regarding the topic of energy-bound surface deformation is described. Boundary conditions and definitions for an analytical model are proposed and consolidated in an analytical equation to determine the energy needed for sufficient plastic deformation. The theoretically determined dependence of the energy threshold on basic tool and workpiece characteristics is validated against experiments. Spherical indenters made of hard metal are dropped on the surface of cast iron and tool steel. Indentation diameters are evaluated according to the initial surface roughness and impact energy. Finally, the analytically predicted and experimentally measured results are compared and discussed.

4. Existing work and boundary conditions for dynamic energy bound processes

MHP provokes a plastic deformation of a rough workpiece surface with comparatively high strain rates. To determine the parameters needed for successful surface treatment, an analytical model of the dynamic contact between rough surfaces is required. Several authors examine the contact between two bodies under different boundary conditions. While Hertz [8] describes the contact of ideally elastic and smooth bodies with no plastic deformation, Johnson derives an analytical model for a dynamic contact of smooth bodies undergoing plastic deformation [9]. Tabor creates an analytical model for the static contact and plastically deformed rough surfaces [10]. The numerical models of Kimura, Childs [11] and Wied [4] consider dynamic contacts and rough surfaces, but are no longer solvable analytically. Also, results for the dependence of the flow stress on strain rates from Goldman [12] remain mostly unconsidered. Existing models thus fail due to incompatibility of the boundary conditions. Besides the conditions mentioned, a threshold value for the smoothing of a rough surface has to be defined.

To define this threshold, the surface asperities are idealized as triangular prisms with a squared base evenly distributed over the surface area. Their height corresponds with the roughness value R_z. To smooth the surface, the prisms have to be formed into cuboids with the same base area (Fig. 1). This is modeled by compression and plastic deformation of the triangular prisms to 0.5 times their initial height. Due to the large area ratio of the spherical indenter to the surface asperities, the assumption to form a cuboid is reasonable.

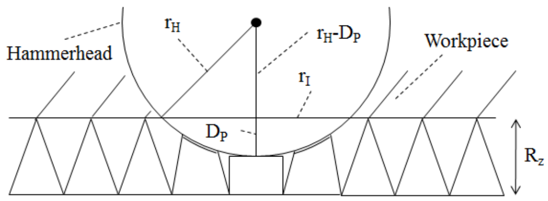

Fig. 1. Boundary conditions for a spherical indenter (not true to scale)

As Kimura and Childs [11] prove in their work, approximately 30 % of the asperities persist after a plastic deformation by a spherical indenter. Transforming this into a factor (1/0.7), it can be stated that the depth of penetration has to be

$$D_P = 0.5 \times \frac{1}{0.7} R_z \quad (1)$$

in order to deform surface asperities. The initial value for R_z can be estimated from surface roughness measurements.

Using the geometric conditions shown in Fig. 1, the radius of the indentation area can be described by

$$r_I = \sqrt{{r_H}^2 - (r_H - D_P)^2} \quad (2)$$

These boundary conditions can be used for the analysis of the problem and derivation of a calculated energy threshold in the following section.

5. Analysis

To simplify the determination of motion characteristics for the impact process, an energy budget is considered. The threshold energy E_T needed for the process consists of an elastic share E_E and a share for the plastic deformation E_P of the surface (Equation 3).

$$E_T = E_E + E_P \quad (3)$$

According to [9], friction and thermal energy can be neglected for central non-rotational impacts. The share of plastic energy is determined from Leeb-Hardness (HLD) measurements as follows, where e is the coefficient of restitution.

$$E_T = \left(\frac{1}{(1 - e^2)} \right) E_P \quad (4)$$

Starting with equation 4, it is possible to calculate the energy needed for a single impact of a sphere depending on the coefficient of restitution e and the energy needed for plastic deformation of the workpiece material. Since E_P is unknown, it is derived in the following. According to [13], the forming energy is calculated by the product of the mean flow stress Y_{SM}, the degree of deformation φ_r and the material volume, characterized by depth D_P and area of indentation A_I. η is the forming efficiency.

$$E_P = \frac{1}{\eta} A_I D_P Y_{SM} \varphi_r \quad (5)$$

For rough surfaces, a contact ratio is calculated from the indenters' roughness R_{zI} and the workpiece roughness R_z (Equation 6).

$$E_P = \frac{1}{\eta} A_I \frac{(0.001 + R_{zI})}{(0.001 + R_z)} D_P Y_{SM} \varphi_r \qquad (6)$$

For smooth workpieces with a similar surface as the indenter, the ratio comes close to 1. For rough workpiece surfaces the contact ratio decreases. Typical values for the indenter roughness lie around 1 µm. The same can be assumed as a minimum for the workpiece, whereas milled surfaces usually show a significantly higher roughness. A_I is defined by the radius r_I calculated from the boundary conditions. The mean flow stress of a material is generally influenced by the flow stress $R_{P0,2}$ and the flow stress after strain hardening through the forming process [13]. Here, the influence of the forming rate according to [14] and [12] has to be considered. The flow stress under impact conditions is therefore defined as R_{PI} and averaged with the flow stress at the end of the forming operation (4 R_{PI}) according to [15] (Equation 7).

$$Y_{SM} = \frac{R_{PI} + 4R_{PI}}{2} \qquad (7)$$

The forming degree is calculated from the radius of indentation r_I and the radius r_0 that corresponds with the area of the Hertzian contact at yield strength. The Hertzian contact includes the Young's modulus of the workpiece (E_1) and the indenter (E_2) according to Equation (8). As the variation of the cross-section of the triangular prism is the dominating variable of the forming operation, the calculation of the degree of forming as a function of the ratio of r_I and r_0 is reasonable.

$$\varphi_r = \ln\frac{r_1}{r_0} = \ln\frac{\sqrt{\left(r_H{}^2 - (r_H - D_P)^2\right)}}{\left(0.683\dfrac{\pi R_{p0.2} r_H (E_1 + E_2)}{E_1 E_2}\right)} \qquad (8)$$

By substituting all the unknown variables, the energy threshold can be calculated.

$$E_T = \left(\frac{1}{(1-e^2)}\right)\frac{1}{\eta}\left(r_H{}^2 - (r_H - D_P)^2\right) \pi \frac{(0.001 + R_{zI})}{(0.001 + R_z)} D_P \frac{R_{PI} + 4R_{pI}}{2} \ln\frac{r_1}{r_0} \qquad (9)$$

For a validation of the equation, different workpiece materials and surface states are investigated by impact experiments.

6. Validation

To validate the analytical model, a spherical indenter is dropped from different heights and hits the surface with a defined kinetic energy. The indentation diameters are measured and a correlation between the area of indentation, surface roughness, radius of the indenter and different material parameters can be deduced.

6.1. Experimental Setup and Matrix

A base plate is used to constrain all components necessary for the impact experiments. A vertical beam is attached by mounting brackets, holding a horizontal crossbeam with an electromagnetic holding device. The specimen is aligned horizontally with bolts and has a form fit with the base plate. Tungsten spheres are dropped from five different heights (energy levels). Calculated by the volume and density, the five energy levels lie between 3.07 mJ and 49.12 mJ, doubling at intermediate steps. The starting height is 40 mm. For each height, the sphere is dropped three times onto different surface locations and results are analyzed statistically.

6.2. Investigated Materials

Two different workpiece materials are investigated. A globular cast iron, material number 0.7070L, and a cold forming steel with material number 1.2379. Leeb-hardness (HLD) is measured according to the standard [16] and the coefficient of restitution is calculated. The material properties are shown in table 1.

Table 1. Material properties of 0.7070L and 1.2379.

Characteristic values / Material	0.7070L	1.2379
HLD [-]	531^{+8}_{-12}	468^{+2}_{-4}
$R_{p0.2}$ [MPa]	445	353
R_{pI} [MPa]	1068	953
E_1 [GPa]	174	215
E_2 [GPa]	550	550

To evaluate the influence of the surface asperities, the specimen are prepared with three different surface conditions. The samples are machined with a 16 mm ball end mill and step over distances between 0.18 mm and 0.70 mm. Thus, different surface roughness characteristics are achieved. The resulting surface parameters are shown in table 2. The indenter has a roughness of R_z=0.9 µm and a diameter of 10 mm.

Table 2. Roughness values for grinded and milled specimen.

Roughness values R_z / Material	0.7070L	1.2379
Milled s=0.18 mm [µm]	$4.3^{+0.1}_{-0.2}$	$5.1^{+0.2}_{-0.1}$
Milled s=0.53 mm [µm]	$8.6^{+0.7}_{-0.5}$	$9.4^{+0.6}_{-0.4}$
Milled s=0.70 mm [µm]	$14.2^{+0.9}_{-1.4}$	$13.4^{+0.7}_{-0.6}$

6.3. Evaluation

The diameters resulting after the deformation are measured with a confocal 3D microscope µsurf® with 20x magnification using the software µsoft® and Hommel Mountains Map®. To determine the diameter of indentations, a circle is measured on the rough surface of the machined specimen. The indentations are measured with a 2x2 stitched image with an area of 1.5x1.5 mm².

7. Results and discussion

The following figures show the diameter of indentation as a function of the impact energy for the experiments performed. Fig. 2 depicts the results for a milled specimen (s=0.53 mm) of material 0.7070L as an example. All other calculations are executed analogous. The data is interpolated with an exponential function and shows a coefficient of determination of about 0.99. For all measurements performed, the lowest coefficient of determination is 0.98.

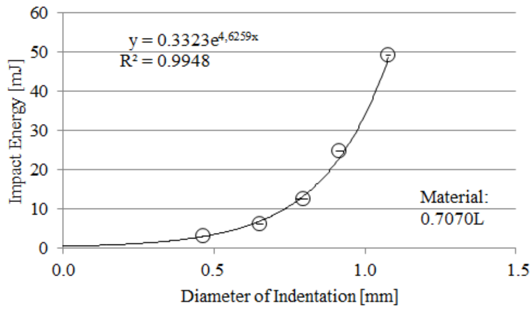

Fig. 2. Diameter of indentation and impact energy for 0.7070L

By inserting the double radius of indentation r_I into Equation 10 (as in Fig. 2), the experimental energy threshold for a specific specimen can be defined. The comparison with calculated values for all specimens and surface states are presented in Fig. 3.

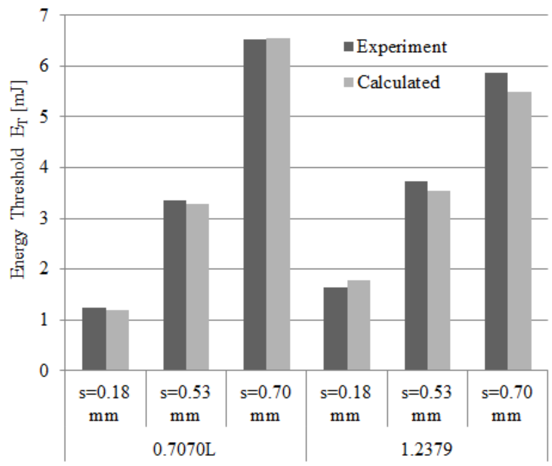

Fig. 3. Comparison of experimental and analytical data

The energy threshold E_T rises with the roughness of the specimen. Furthermore it can be stated that the hardness and yield strength of the materials has a significant influence on the energy threshold.

Due to the small dimension of the deviations between calculated and experimentally determined values (max. 8%) the model is validated. The deviations from the threshold energy may result from different strain hardening behavior of the materials as it is referred to in [4]. Depending on the mechanical properties, material is either drawn into or accumulated around the edge of the indentation.

8. Summary and outlook

An analytical model for the calculation of the required energy input for successful smoothing of surface asperities by MHP has been derived. The validated model allows calculating the energy threshold for different surface states, taking basic tool and workpiece parameters into consideration. Based on this, statements concerning the machinability of various materials and surface characteristics can be derived. This reduces the need to determine parameters by experiment.

To further increase the accuracy of the analytic model, a factor for the strain hardening phenomenon has to be considered.

For the definition of a process window for MHP it is also necessary to define an energy limit to prevent the aforementioned surface defects.

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